LOW COST AND EFFICIENT FLIGHT OPERATIONS SYSTEM FOR SIRTF

Marie-Jose Deutsch
SIRTF Project Office
Jet Propulsion Laboratory
California Institute of Technology[*]

Abstract

The Space Infrared Telescope Facility (SIRTF), the fourth of the Great Observatories, will be placed in a unique solar orbit trailing the Earth, in 2001. SIRTF will acquire both imaging and spectral data using large infrared detector arrays from 3.5mm to 160mm. The primary science objectives are (1) search for and study of brown dwarfs and super planets, (2) discovery and study of protoplanetary debris disks, (3) study of ultraluminous galaxies and active galactic nuclei, and (4) study of the early Universe.

Driven by the limited cryogenic lifetime of 5 years, and the severely cost-capped development, the SIRTF mission has been designed to minimize complexity. A Mission Planning and Operations system is being implemented that will result in high efficiency and low-cost operation, yet will accommodate rapid response to science requirements.

SIRTF's operations architecture is accommodating a shared science and flight operations system. Crucial to this effort is the philosophy of an integrated science and engineering plan, co-location and cross-training of teams and common planning tools.

The common tool set will enable the automatic generation of an integrated and conflict free planned schedule accommodating 20 000 observations and engineering activities a year. The shared tool set will help generate standard observations, engineering activities and manage the ground and flight resources and constraints. The ground in synergy with the flight system will accommodate the development of robust but flexible sequences of activities. The "virtual machine" architecture enables the ground system to take advantage of extra time between observations, and failed observations. Late updates have become trivial and provide great flexibility to incorporate newly discovered science opportunities or health issues late in the process. This shared science and flight operations process will provide a low-cost operations system.

SIRTF being the last of the "Great Observatories" and a precursor in the "Origins" mission series will contribute to the validation of new and improved architectures for astronomy missions at costs more closely resembling those of Explorer class missions.

1. Mission Design Overview

The Space Infrared Telescope Facility (SIRTF), the fourth of the Great Observatories, and a precursor to the ambitious Origins program, is unique in its ingenious technical capabilities and scientific basis for studying the Universe at infrared wavelength. SIRTF will acquire both imaging and spectral data using large infrared detectors arrays from 3.5 to 160 micron. Like many of the missions being proposed and developed at JPL, the SIRTF team at JPL has been actively working with its industrial partners and the instrument teams to design the mission since its rescoping effort in the early 1990s. SIRTF's cost had been reduced from its original budget of $ 2.2 billion to $ 0.45 billion, which

---

brought about a much simpler but just as capable and more operable mission. In the end, SIRTF's simple mission design concept is its greatest asset.
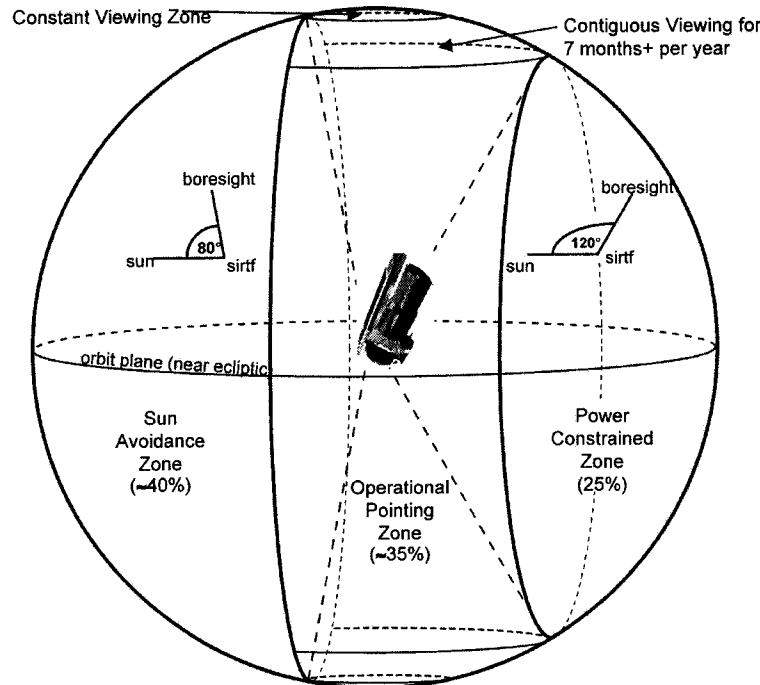
1.1 Orbit and Viewing Constraints

Figure 1. SIRTF's main geometric observing constraints and instantaneous sky visibility

SIRTF will be launched in December 2001 into an Earth trailing heliocentric orbit, drifting away from Earth at a rate slightly higher than .1AU a year. The observatory will have drifted to around .64 AU in 5 years. This orbit is very favorable for both mass and thermal reasons, keeping development and operations costs low. In addition this orbit allows continuous observing without occultations and eclipses providing excellent visibility of roughly 35 % of the sky at all times, contributing to its scientific efficiency. The operational pointing zone (OPZ) is defined as the sun avoidance zone and the power constraint zone (Figure 1). As the observatory orbits the sun, the same area of the sky becomes visible twice a year for a minimum of 40 days if the target is near the ecliptic, for 60 days at an ecliptic latitude greater then 30 degrees, up to seven months of visibility at a latitude of 60 degrees and constant visibility near the ecliptic pole. The enforcement of the OPZ keeps sunlight from striking any cold surface of the telescope and assures that the solar arrays powering the observatory remain well illuminated. The continuous observing sequence is only interrupted for the twice daily downlinks of up to 4 gigabits of compressed data stored in solid state memory. In order to establish the telecommunication link, the observatory is turned such that its high gain antenna which is affixed to the underside of the telescope is pointed toward Earth. Each data communication session takes roughly 30 minutes at a rate of 2.2 Mbps. Commands can be uplinked concurrently at a rate of up to 2 Kbps. Command sequences are uplinked once a week, but each DSN contact provides for an uplink to acknowledge the successful receipt of data and de-allocate the corresponding memory space. The observatory features also an omni low gain antenna, which permits communication with the observatory at almost any time.

2. The flight system

The flight system is composed of a spacecraft, a cryogenically cooled telescope and three instruments. JPL is responsible for project management, system and mission engineering, science management and flight operations. Lockheed-Martin (Sunnyvale, California, USA) is responsible for the development of the spacecraft and integration and test, Ball Aerospace (Boulder, Colorado, USA) is responsible for

the development of the cryogenic telescope assembly including the integration of the three instruments. The Infrared Array Camera (IRAC) is the responsibility of Goddard Space Flight Center and led by SAO-Harvard, Principal Investigator Giovanni Fazio. The Multiband Imaging Photometry for SIRTF (MIPS) is developed at Ball and led by University of Arizona, Principal Investigator George Rieke. The last instrument the Infrared Spectrograph (IRS) is also developed by Ball under the leadership of Cornell University principal Investigator Jim Houk.

The flight system has no moving parts that are used on a regular basis, except for a MIPS internal mirror. The observatory has a focal plane adjustment mechanism, which is not planned on being used, except for contingency purposes. The first week after launch a set of critical activities are performed to deploy the observatory to enable complete cooling of the telescope and operation of the cryogenically cooled instruments. A set of helium valves are opened during launch and right after launch allowing the He vapors to escape and cool the telescope. As soon as the attitude control system has gone through an initial checkout, the telescope dust cover is ejected around day three to permit further radiative cooling of the telescope. And finally the instrument aperture door is opened, to let the light enter the instrument detectors. This very limited set of operating mechanisms simplifies the operation of the mission considerably. It also keeps the risk and cost low.

2.1 Flight Software

The flight software of the command and data handling system **is inherited** from Mars 98 and has become multi-mission software used on many Lockheed-Martin built spacecrafts. The pointing control system software is also inherited from Lockheed-Martin. This presented an initial simplification and cost saving. However, the software is also being heavily adapted to the SIRTF mission. In particular, the fault detection, isolation and recovery software, the software driving the interfaces to the telescope and the interfaces with the instruments, the pointing control algorithms supporting the instrument modes and the sequence machine language are mostly new development.

a) The **fault protection** software on SIRTF is driven by efficiency requirements for high science return (90% of the time reserved for science observations) and by the flight system survivability. This has led to a multi-layered fault response system of the observatory. Some fault remedies do not interfere with the on-going sequence. These are the type of failure where a **back-up or redundant system is used** when the primary system fails. This failure does not imply any loss of science data. The second type of fault response, stops the sequence and puts the spacecraft into a **stand-by mode**. This mode also puts the instruments in suspend mode or if an instrument is the cause of the failure, turns the instrument off. This state is fairly benign from recovery point of view, because it leaves most of the observatory states intact and provides high communication link to the ground. Within a very short period of time the ground system should have identified and fixed the problem and be able to resume science observations. No instrument failure shall bring the observatory into a fault protection state "deeper" than the stand-by mode. The third type of fault response is the **safe mode**. It occurs in response to a more serious fault on board the spacecraft, that requires immediate halting of the sequence and brings the spacecraft into a state requiring minimum power, turning off all non essential loads e.g. instruments, points the Z axis at the sun and operates the PCS on sun sensors only, rotating the observatory about the Z axis. The telecommunication link is minimized to the low gain antenna. The ground system receives each hour at least 20 minutes worth of low bit rate data, as its LGA rotates through the Earth cone angle.

b) The **pointing control modes** and modeling changes for this observatory turn out to be significant.
- The Pointing Control System (PCS) is used to control the orientation of the boresight of the telescope in absolute and relative position. PCS provides the capability for large angle slews between targets as well as short angle slews to place the target into the field of view of the instruments. PCS provides four basic modes that help science observation gathering: inertial pointing, incremental pointing, scan map and tracking.

- During inertial pointing the boresight is kept inertially fixed on a target. This mode is used to perform long integration on faint targets. The absolute pointing accuracy required to be 5 arcsec is now projected to be 1.3 arcsec with a stability of 0.3 arcsec over 200 seconds.
- The incremental pointing mode performs small repositioning of the boresight with an accuracy of 0.4 arcsec across angular distances of up to 30 arcmin. This mode is used to accomplish the super-resolution mode and to move science targets within the focal plane.
- The scan map mode slews the observatory at a constant rate between 2 and 20 arcsec/s with a scan stability of 0.7 arcsec in 15 s and scan rate accuracy of 3 % of the commanded rate. This mode is used for efficient mapping of large areas with the MIPS.
- In the tracking mode the observatory boresight follows a precomputed time-tagged target at rates of up to 1 arcsec/s to perform solar system object tracking. PCS simulations indicate that the tracking acquisition accuracy is < 2 arcsec and the stability is ~ .5 arcsec in 1000 s. The offset accuarcy during tracking ~ 0.4 arcsec.

- The flight algorithms and ground models simulating the pointing modes, slews and settling times are considerable. The models used for simulation and ground checking are the same and as close as possible to the flight algorithms themselves. This gives the scientists predictive capabilities allowing accurate pointing system behavior and timing of observations. After Launch these models are planned to be updated to reflect the behavior of the pointing system in flight.

c) The **sequence engine** is an on-board construct that provides the ground with a way of commanding the observatory in a time ordered fashion, controlling the execution of observations and the behavior of the observatory. The language provided to the ground to build commands and sequences is inherited from M98. However, the capabilities of this low level language, akin to assembler language, do not meet SIRTF's requirements for more efficiency and the complex logic used to build the science activities. A new *language* and sequence engine, the *virtual machine,* is used to emulate an environment allowing for higher level language constructs, logic such as conditional executions and branching, and functions permitting the passing of parameters, return values. The language permits global variable setting by the sequence and triggers of the flight system and its sensors causing event driven actions to take place within the sequence. The virtual machine language used with the virtual machine capabilities, gives science the ability to build logic intensive science activities and provides them with the additional flexibility of scheduling science activities more tightly, even oversubscribing the sequences with activities. If a sequence fails to finish executing on time, that sequence is terminated and after appropriate clean-up, proceeds to the next sequence. Rather than build one long non interruptible sequence that executes for many days, SIRTF is implementing a scheme that features a week long "master" sequence with many calls to "slave "sequences. The slave sequences can be as short as one activity or as long as the master sequence. Each sequence is a file that can be updated as long as it has not started to execute or interfere with the ongoing master sequence. This scheme is used in the case of a target of opportunity. When a target of opportunity arises, a slave sequence file that has not yet started to execute will be replaced with a file containing the observation of the target of opportunity. This process will allow for very rapid updates estimated to be as short as 24 hours since the discovery of the special target. This efficiency will allow SIRTF to "catch" super novae explosions and other fast changing phenomena.

2.2 Warm launch

SIRTF will be launched at ambient temperature and allowed to radiatively (passively) cool in space within a few weeks after launch. Only the instrument detectors and the cryostat are encased in a vacuum shell, which contains a 360-liter superfluid helium tank that cools the multiple instrument chamber. (MIC) (Figure 2) In this design, the in-orbit parasitic heat load to the cryostat is substantially reduced, leading to a dramatic reduction in the volume of liquid cryogen required. [For comparison's sake, IRAS used 520 liters over 10 months, and ISO's 30-month mission utilized 2140 liters.] The liquid Helium bath will serve as heat sink and remain at 1.5 degree K while the helium boil-off will cool the inner telescope assembly down to 5.5 degree K. The outer shell temperature will reach ~ 33deg K. The observatory will at all times remain oriented such that the solar panel will

shield the CTA from sun light. This innovative design has allowed SIRTF project to considerably reduce its mass and launch on a Delta 7920H two stage launcher.
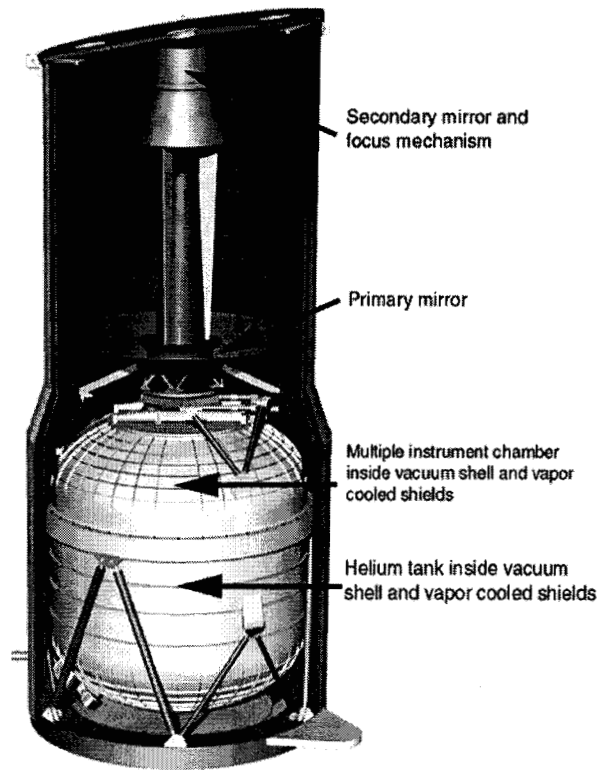
Secondary mirror and focus mechanism

Primary mirror

Multiple instrument chamber inside vacuum shell and vapor cooled shields

Helium tank inside vacuum shell and vapor cooled shields

Figure 2. SIRTF Warm Launch Architecture

2.3 Instrument overview

SIRTF has benefited from a real revolution in infrared detector technology brought about by industry, which served military interests in developing detectors for high-background temperature environments in wavelengths shorter than 30 μm. Astronomers have adapted this technology to their needs for low-background and high sensitivity sky observations in the infrared up to 200 μm. SIRTF will feature a thousand-fold increase in sensitivity. In addition the size of the arrays has increased many thousands of times as well. The benefit of the high sensitivity and large arrays of detectors is that observations can use short integration time, thus increasing the observatory efficiency.(Figure 3)

The MIC is encased in the vacuum shell with the cryostat. The primary and secondary mirrors redirect the incoming light onto the detectors after the aperture door has been opened early in the mission. SIRTF features three instruments, which provide imaging, photometry and spectroscopy. The focal plane field of view with a diameter of 31.7 arcmin shows 10 instrument field of views associated with the three instruments. All instruments view the sky concurrently, but only one instrument is operational at a time. Table 1 summarizes the instrument capabilities.

The Infrared Array Camera (IRAC)} is a four-channel large field imaging camera, which observes simultaneously at 3.6, 4.5, 5.8, and 8μm. On the focal plane there will be two 5.12 x 5.12 arcmin. images which view the channels in pairs of 3.6 and 5.8 μm in one field of view (FOV) and 4.5 and 8.0 μm in the other FOV. The arrays have each a size of 256 by 256 pixels. The two short wave channels use InSb detectors while the two longer wave channels use Si:As IBC detectors. IRAC will address the scientific objectives defined for SIRTF, but will also be used as general-purpose camera for a wide variety of astronomical programs.
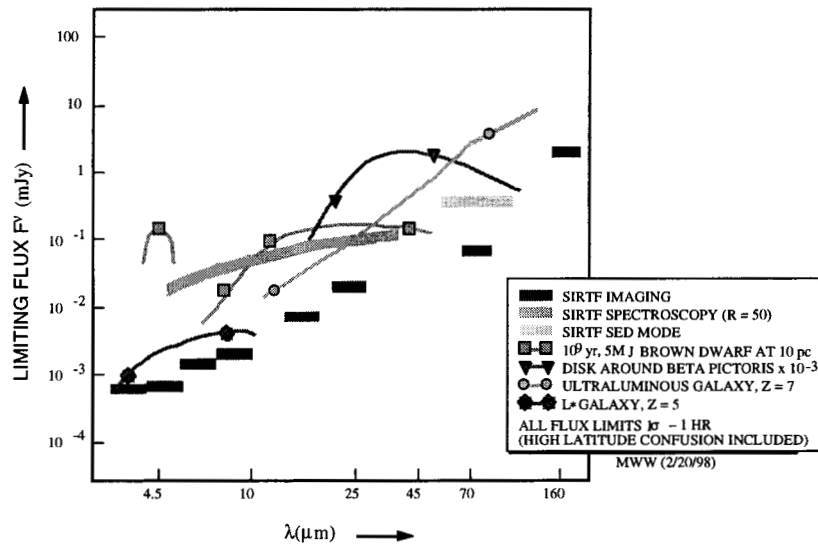
Figure 3 SIRTF Sensitivity

The Multiband Imaging Photometry for SIRTF (MIPS) is comprised of three detector arrays. The arrays are a 128x128-pixel arsenic-doped silicon (Si:As) for imaging at a wavelength of 24 μm, a 32x32 gallium-doped germanium (Ge:Ga) at 70 μm, and a 2x20 stressed Ge:Ga array at 160 μm. These arrays are optimized for efficient large area surveys and superresolution programs. The 32x32 array also takes very low-resolution spectra from 50-100 μm and has a resolution of R ~ 15. MIPS will carry out the following observations: deep field mapping of large areas, photometry of compact sources, super resolution imaging, measurement of spectral energy distributions at low spectral resolution, and total power measurement.

SIRTF Instrument Summary

Wavelength (microns)	Array Type	Resolving Power	Field of View	Pixel Size (arcsec)	Sensitivity (micro-Jy) 5σ in 500 s, inc. confusion
Irac: Infrared Array Camera					
3.6	InSb	5	5'x5'	1.2	5
4.5	InSb	4	5'x5'	1.2	5
5.8	Si:As(IBC)	4	5'x5'	1.2	23
8	Si:As(IBC)	3	5'x5'	1.2	34
MIPS: Multiband Imaging Photometer for SIRTF					
24	Si:As(IBC)	4	5'x5'	2.4	370
70	Ge:Ga	4	2.6'x2.6'/5'x5'	4.9/9.4	1400
50-95	Ge:Ga	20	18".8x4'	9.4	6500
160	Ge:Gs(stressed)	4	0.5'x0.5'	15	22.5 mJy
IRS: Infrared Spectrograph					
$\leq$5-15	Si:As(IBC)	50	3.6"x55"	1.8	550
15(Peakup)	Si:As(IBC)	2	1'x1.2'	1.8	100
10-20	Si:As(IBC)	600	4.8"x12.1'	2.4	3x10e-18 W/m2
15-40	Si:As(IBC)	50	9.7"x145"	4.8	1500
20-38	Si:As(IBC)	600	9.7"x24.2"	4.8	3x10e-18 W/m2

The InfraRed Spectrograph (IRS) has four separate modules or cold assemblies. High efficiency grating and echelle spectrographs are used in conjunction with 128x128 pixel Si:As and Si:Sb BIB

arrays. The high resolution spectra, Short Hi and Long Hi modules cover 10 to 19.5 μm and 19.5 to 38 μm respectively with a spectral resolution of 600. The low resolution spectra, Short Lo covers 5 to 15 μm while the Long Lo module covers 14 to 40 μm with a spectral resolution R = 50. In addition the Short Lo module contains a large field of view, the peak-up array, used to image poorly known sources and locate them precisely for subsequent accurate placement in the spectrograph slits. The IRS is used for diagnostic observations on previously known sources or freshly discovered SIRTF sources.

The Pointing Calibration and Reference Sensors (PCRS) located in the MIC are also located in the focal plane. These sensors are used to calibrate any mis-alignment caused to thermo-mechanical effects between the telescope focal plane boresight and the to star tracker boresight.

3. Ground System

The Ground system is composed of the flight Operations System (FOS) and the Science Operations System (SOS). JPL is managing the development and operations of the FOS, while the SOS is developed and operated from the SIRTF Science Center (SSC) at Caltech.

3.1 Flight-Ground Interfaces and End-to-End Data System

Starting as early as phase A when the observatory design was established, the ground system (GS) was actively participating in the design of the flight system (FS), especially the flight software aspects including the instrument common electronics software and interfaces between the Spacecraft, the Instruments, the Telescope and the GS. From this concurrent design effort emerged four documents that drive both the ground system and the flight system design. The Flight-Ground Interface Control Document (FGICD) controls the division of responsibility between the GS and FS. The Observatory Performance and ICD (PICD) controls the division of responsibility within the FS. (e.g. instruments, telescope and spacecraft) The Fault Protection Design Document (FPDD) controls the design of the on-board fault responses and the Facility Data System (FDS) Integration and Verification Plan ensures end to end verification of the entire flight and ground software system. These documents spell out the requirements levied on the GS, however big design drivers on the GS were identified and remedied early on and the observatory operability was ensured from the start.

3.2 Integrated mission planning, scheduling and sequencing team

Even thought the flight and science operations are separate organizations, lessons learned from other observatories e.g. HST and ISO, compelled SIRTF to design a common set of tools and processes used by a physically collocated and integrated mission planning, scheduling and sequencing team (IMPST) composed of members from both FOS and SOS. The interfaces governing this relationship are captured in the Science and Flight Operations ICD (S&FO_ICD). The expected efficiency gained through this common process allows SIRTF's operations team to remain small compared to the other Observatories.

3.3 The Process

The operations process used by SIRTF is a combination of JPL inherited processes used mostly during the integration and sequencing aspects of engineering and science activities, while the lessons learned from HST and ISO are factored heavily into the process design for the planning and scheduling aspects.

The SIRTF design allows only one instrument to be operated at a time on a rotating basis for a period of 3 to 7 days when the next instrument starts observing. Science observations are going to be performed by means of seven observing modes. Each observing mode allows the user to unambiguously define the parameters of their observations. These modes are the basic science building blocks for observing with SIRTF. IRAC has one observing mode for mapping and photometry in all 4 detectors. IRS features two observing modes, the staring mode spectroscopy and spectral mapping. While MIPS has the scan map mode for mapping of large areas on the sky,

photometry and super resolution mode, the spectral energy distribution mode and the total power mode. Both science and engineering calibrations are performed using standard parameterized "blocks" of commands.

The planning process on the science side involves the identification and selection of observations visible during a roughly 40-day period, which also corresponds to the available viewing window. These observations are placed on a rolling basis in a database and are accessed weekly for scheduling into a conflict free sequence with the engineering activities. The pool of observations available each week is typically oversubscribed for scheduling efficiency purposes. Various scheduling algorithms are used to devise an optimum and conflict free schedule. These algorithms are both inherited from HST and involve new development. Since few engineering activities are planned, except for the routine engineering calibrations, communication sessions with the grounds and momentum unloads, the schedule is not expected to present conflicts between science and engineering activities.

The integration and sequencing processes follow the nominal TMOD multi-mission operations processes.

3.4 The Tools

Science observing modes are programmed into standard building blocks, which are tested and simulated over a range of parameter values before launch. Engineering activities too are programmed into blocks. The science astronomical observing requests (AORs) for a given instrument are designed to be independently initialized and can be put in any order into the schedule without additional "make play" commands. This allows a schedule and sequence to be generated in minutes using our automated scheduling and sequencing software.
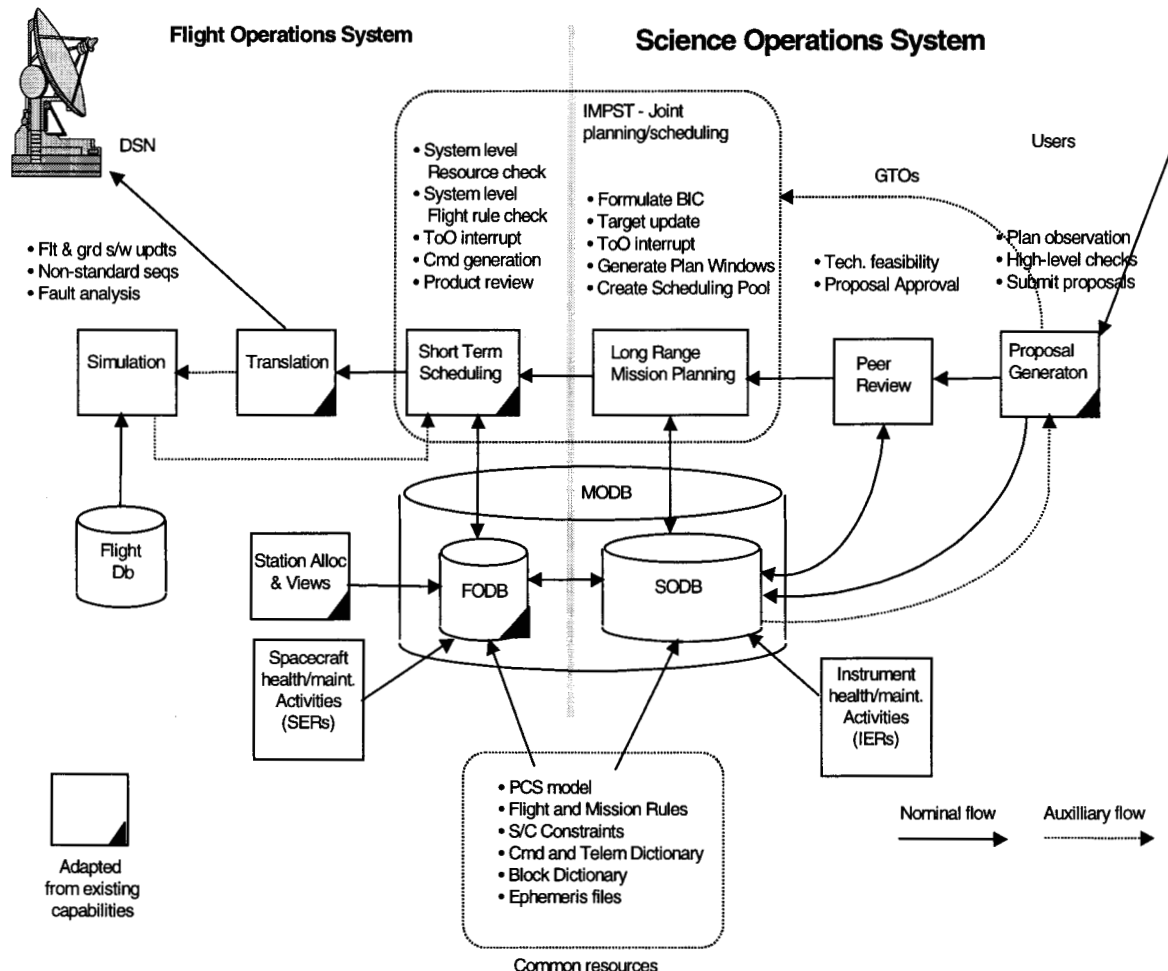

Figure 4. Ground System Uplink Data Flow

8

SIRPASS, a new semi-automated planning tool can be used for long term strategic and short term tactical planning. The tool is partly inherited from Mars Pathfinder (Plan-IT) and from HST. (Spike) SIRPASS plans activities according to a set of scheduling algorithm into conflict free schedule. It checks all system level flight rules and resources. The outputs from SIRPASS are passed into the TMOD Uplink tool kit for expansion and further checking at the command level. The only new feature of the TMOD Uplink tool kit is the changes made as a result of the virtual machine requirements. Figure 4 illustrates the SIRTF Ground Data System and Figure 5 shows the upgraded TMOD Uplink Tool kit.

Pointing Control models are developed by FOS and delivered to SSC for use with the modeling and checking of AORs. These models are also used by SIRPASS to determine the slew profile from one target to the next and by the Uplink tool kit to check PCS constraints. The same model/algorithm is used from end to end including the simulator and the spacecraft.
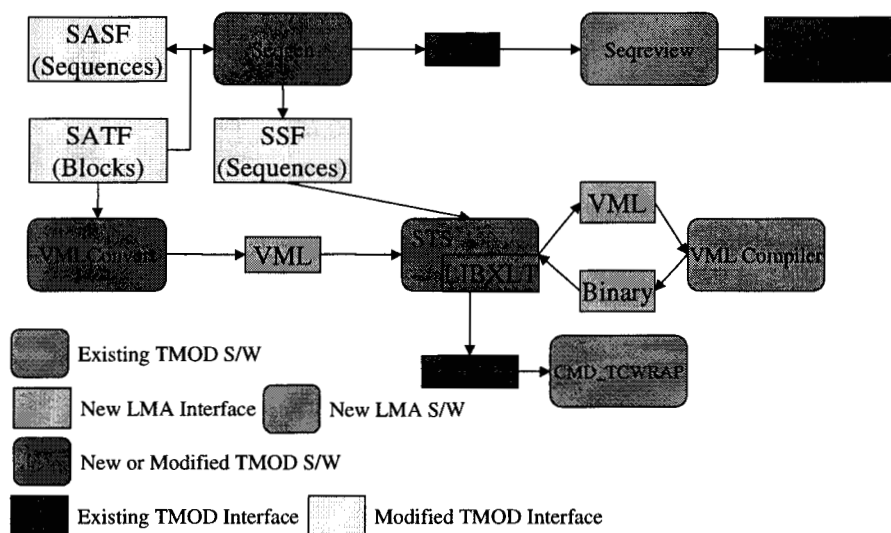
Figure 5. Upgraded TMOD Uplink Tool kit for use by SIRTF

The entire uplink process is being automated through the use of scripts. All steps that can be automated, will. The steps requiring human decision making are brought to the attention of the correct decision makers via e-mail. This system is inherited from MSOP and adapted by TMOD.

4. Implementation and Testing

Implementation and testing is not handled as two separate steps, but happen on a continual basis. "Implement a little, test a little" is the SIRTF motto. Testing is done on the whole end to end system integrating the flight and ground system in the process. This type of testing was started using the data system first, since it is being developed ahead of the procedures. On six months intervals the Facility Data System (FDS) incorporating new capabilities during each test phase, runs a series of end-to end tests involving the on-board software system and ground software system. This method has been extremely useful in flushing out problems early with the instruments and with the flight software. As the processes and procedures are being developed, these too will be incorporated into the end-to-end test leading up to verification and validation of the whole SIRTF system and its readiness for launch. Standard observations, blocks and sequences are checked in ground software are tested on the simulator. The simulator is a hardware simulator of the SIRTF C&DH with Instrument Engineering Units and functional models of the Pointing Control System. After thorough simulation, a selected set of blocks and sequences, including all AORs and critical sequences are run through the Assembly Test

& Launch Operations (ATLO). All Initial Observatory Check-out (IOC) sequences and representative sets of science sequences are developed and tested/simulated ahead of time giving the operations teams ample hands on operations experience.

5.0 Contingency Planning

SIRTF is in the process of carefully planning the critical activities during Launch and IOC. A fault tree analysis is performed for each critical activity including many of the activities leading up to and providing the initial conditions for the critical activities. Contingency plans, procedures and commands are developed and simulated ahead of time and placed "on the shelf" for potential use.

6.0 Conclusion

The SIRTF mission has been designed for simplicity and efficiency, in a very constrained budget environment. Lessons learned from other observatories have been folded into the design. SIRTF is also remedying problems discovered during recent missions to mars. However, despite the vigilance many challenges remain to be overcome as the observatory integration and test proceeds and operations development evolves and is verified and validated with the flight team on the flight vehicle.

5.0 References

[1] Deutsch, M.J., Bicay, M.D., "Observing with SIRTF: Opportunities for the Scientific Community", proceedings from the 8th UN/ESA workshop on Basic Space Science, Al al Bayt University, Jordan, March 1999, Astrophysics and Space Science, Kluwer Academic Publishers, 2000.

[2] Brown, G.M., Day, J.C., "Autonomy Requirements for the Space Infrared Telescope Facility", …

[3] Deutsch, M.J., Ebersole, M., Nichols, J., Bicay, M., Garcia, M., Kahr, J., Mittman, D., "Low-Cost Flight Operations System for SIRTF", Display Session 42, American Astronomical Society 191st Meeting, Washington, D.C., January 1998. (Bulletin of the AAS, 1997, Volume 29 #5)